Physical-Biological-Optics Model Development and Simulation for the Monterey Bay, California

Fei Chai
School of Marine Sciences, 5706 Aubert Hall
University of Maine, Orono, Maine 04469
phone: (207) 581-4317 fax: (207) 581-4990 email: fchai@maine.edu

Emmanuel Boss
School of Marine Sciences, 5706 Aubert Hall
University of Maine, Orono, ME 04469
phone: (207) 581-4378 fax: (207) 581-4990 email: emmanuel.boss@maine.edu

Award Number: N00014-08-1-0273
http://rocky.umeoce.maine.edu/
http://misclab.umeoce.maine.edu/

LONG-TERM GOALS

Modeling and predicting ocean optical properties for coastal waters requires linking optical properties with the physical, chemical, and biological processes in the upper ocean. Our long-term goal is to incorporate optical processes into coupled physical-biological models for coastal waters, develop and improve integrated ocean forecasting systems, including prediction of ocean optical properties.

OBJECTIVES

1) To improve performance of the coupled physical-biological model, which is based on the Navy Coastal Ocean Model (NCOM) and Regional Ocean Model System (ROMS) for the California Current System (CCS);

2) To incorporate optical variables into the improved coupled 3D physical-biological model for the CCS;

3) To use these variables to drive a radiative transfer model (EcoLight) that will simulate and predict the subsurface light field as well as the ocean's color;

4) To conduct NCOM-biological-optical model simulations for the Monterey Bay for the period of the intensive field experiments, such as BioSpace in Monterey Bay 2008 (June 2008), and use the bio-optical measurements to constrain and improve the model performance.

APPROACH

To achieve the first objective, we have conducted a series of 3D physial-biological model simulations for the California Current System. We have incorporated the Carbon, Silicate, and Nitrogen Ecosystem (CoSiNE) model into both the Navy Coastal Ocean Model (NCOM) and Regional Ocean Model System (ROMS). The CoSiNE model (Chai et al., 2002; 2003, and 2007) was developed originally for

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Physical-Biological-Optics Model Development and Simulation for the Monterey Bay, California**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Maine,School of Marine Sciences,5706 Aubert Hall,Orono,ME,04469**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

the equatorial and Pacific Ocean. During the past three years, we have implemented the CoSiNE model and improved the performance for the CCS, and investigated the seasonal and interannual variation of biological productivity in response to both local and remote climate forcing.

For the optical modeling work, our approach is to incorporate spectrally-resolved inherent optical properties into the existing NCOM-CoSiNE and ROMS-CoSiNE model which haven't included the optical processes and in-water radiative transfer model for the California Current System (see Figure 1). We have successfully incorporated an optical module along with a commercially available radiative transfer model (EcoLight) into a one-dimensional ecosystem model which is flexible enough that can be applied to three-dimensional circulation model (Fujii et al., 2007). This effort illustrates the value of adding optical processes into physical-biological models. Based on this experience, we developed an optical model that is fully compatible with NCOM-CoSiNE model for the California Current System. The optical model explicitly represents spectrally-resolved inherent optical properties (IOPs) including absorption, scattering, and attenuation. The optical model requires input from NCOM-CoSiNE model, such as phytoplankton associated chlorophyll and non-algal particles (NAP), and it provides outputs such as phytoplankton absorption coefficient, detritus absorption coefficient, particulate backscattering coefficient. These optical products are all spectrally-resolved and can be compared with satellite and in situ data directly.

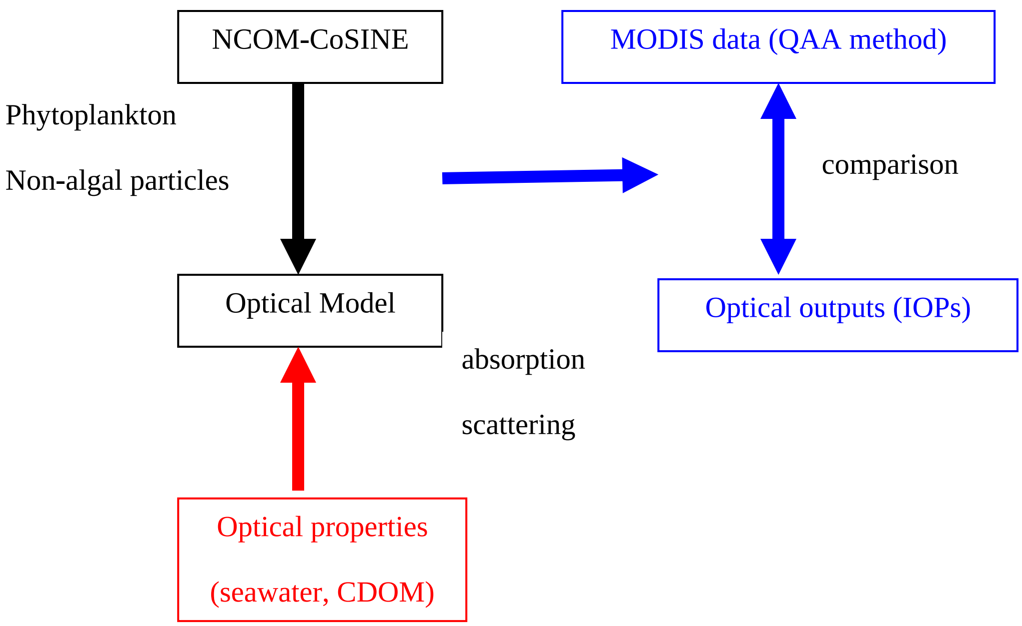

Figure 1: Overall approach for incorporating optical properties into NCOM-CoSiNE model. The effect of CDOM in the optical model is a constant at present, but will be modeled dynamically in the next phase of the project.

In the optical model, absorption coefficient is determined from the sum of the absorption coefficients of seawater, phytoplankton (based on the chlorophyll content of pico-plankton and diatoms, respectively), NAP, and CDOM. Seawater absorption coefficient is modeled based on previous observations (Pope and Fry, 1997; Morel, 1974). Phytoplankton absorption is calculated as the sum of pico-plankton and diatoms with different chlorophyll-specific absorption coefficients due to the different sizes of them. Pico-plankton has a higher chlorophyll-specific absorption coefficient and a steeper absorption spectra than diatoms. In addition, the absorption spectra of a given phytoplankton functional group changes with intercellular chlorophyll concentration (the package effect). Therefore, the chlorophyll-specific absorption coefficients by pico-plankton and diatoms are modeled separately:

$$a_{\phi}(\lambda, z) = a^{*}_{\phi 1}(\lambda, z) \times chl1(z) + a^{*}_{\phi 2}(\lambda, z) \times chl2(z) \qquad (1)$$

where chl1 and chl2 are chlorophyll concentration for pico-plankton and diatoms converted from modeled biomass. A photo-acclimation model is included to include the light adaptation effects on chlorophyll/carbon ratio.

Color dissolved organic matter (CDOM) also plays important role in absorption spectra. We fix its absorption coefficient at 440nm vertically to be 0.016 (m^{-1}), which is within observed range (0.012-0.019 (m^{-1}), Simeon et al., 2003). We do so, as the first step, because the current version of NCOM-CoSiNE model has not included active CDOM dynamics and ratios of CDOM to dissolved organic matter (DOM) or dissolved organic carbon (DOC), and these processes vary greatly in the CCS. In the optical model, CDOM absorption spectra is assumed constant vertically and with a spectral dependence:

$$a_{CDOM}(\lambda) = 0.016 \times \exp\{-0.0145 \times (\lambda - 440)\} \qquad (2)$$

NAP absorption follows a similar manner to CDOM, and is expressed as:

$$a_{NAP}(\lambda, z) = a^{+}_{NAP}(440) \times NAP(z) \times \exp\{-0.011 \times (\lambda - 440)\} \qquad (3)$$

where $a_{NAP}^{+}(440)$ is the carbon-specific absorption coefficient by NAP at 440nm which is assumed to be 0.1 ($m^2\ gC^{-1}$) based on observations (Babin et al., 2003).

In the optical model, assuming no contribution of CDOM to backscattering, backscattering coefficient is determined as the sum of seawater, algae and co-varying particles. Algae and co-varying particles are expressed as a function of particulate organic carbon concentration (POC) of small and large particles, which consist of pico-plankton, diatoms, and associated NAP, respectively. Backscattering by small and large POC (POC1 and POC2) are formulated as follows (Stramski et al., 1999):

$$b_{bp1}(\lambda, z) = \left(\frac{POC1(z)}{476935.8}\right)^{\frac{1}{1.277}} \times \left(\frac{\lambda}{510}\right)^{-0.5} \qquad (4)$$

$$b_{bp2}(\lambda, z) = \left(\frac{POC2(z)}{17069.0}\right)^{\frac{1}{0.859}} \qquad (5)$$

The total backscattering coefficient is calculated

$$b_b(\lambda, z) = 0.5 b_{sw}(\lambda) + b_{bp1}(\lambda, z) + b_{bp2}(\lambda, z) + b_{bbg} \qquad (6)$$

where $b_{sw}(\lambda)$ is seawater scattering coefficient with the correction for salts (Boss and Pegau, 2001). b_{bbg} is the background backscattering coefficient the implicitly reflects contributions by non-phytoplankton-covarying bacteria and other particles (Behrenfeld et al., 2005).

WORK COMPLETED

This report summarizes modeling activities between 1 January 2008 and 30 September 2008.

We have completed the following modeling tasks:

1. Evaluated the performance of 3D physical-ecosystem model for the California Current System (CCS) with the observations from the Californian Cooperative Ocean and Fisheries Investigation (CalCOFI) and Monterey Bay Aquarium Research Institute (MBARI);
2. Linked the bio-optical module, based on 1D configuration (Fujii et al., 2007), with the Carbon, Silicate, Nitrogen, and Ecosystem (CoSiNE) model for the CCS;
3. Incorporated bio-optical module and CoSiNE into the Navy Coastal Ocean Model (NCOM) for the California Current System (CCS), and the Regional Ocean Model System (ROMS) for the Pacific Ocean;
4. Conduct a series of model simulations to test the robustness of the NCOM-CoSiNE-Optics and ROMS-CoSiNE-Optics for various regions;
5. Started to evaluate model performance with remote sensing derived IOPs for the CCS.

RESULTS

We have conducted a series of the ROMS-CoSiNE model, without the optical component, for the California Current System for the period of 1990-2005. For doing so, we can evaluate the ROMS-CoSiNE model performance with the long term time series observations from the Californian Cooperative Ocean and Fisheries Investigation (CalCOFI) and Monterey Bay Aquarium Research Institute (MBARI). First, compare the modeled physical and biological variables on the annual mean basis, then evaluate the seasonal cycle of nutrient dynamics and biological productivity. The CalCOFI and MBARI observations are grouped into six dynamically different regions according to near-shore upwelling areas vs. off-shore less productive regions, Figure 2.

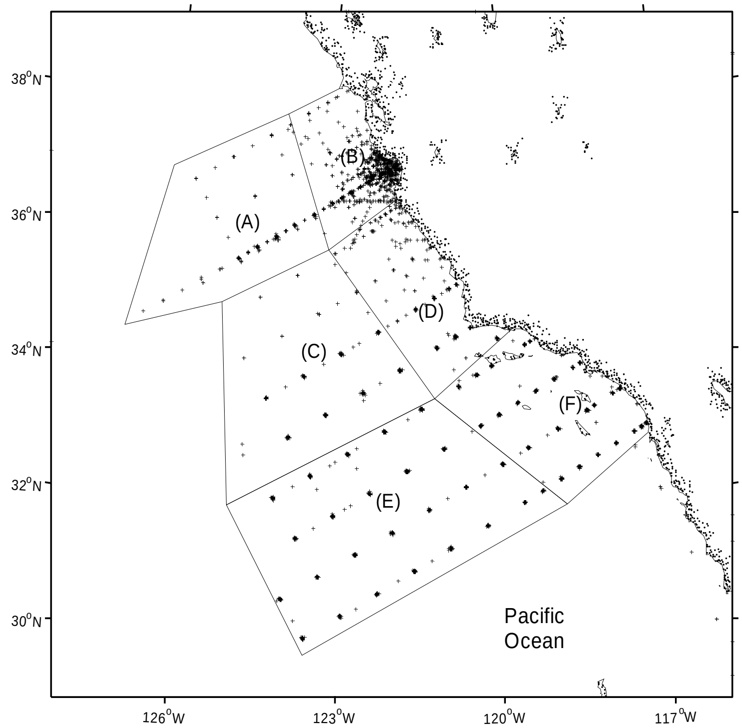

Figure 2: Long term CalCOFI and MBARI observations for the central California regions. Up to 166,612 profiles of measurements from CTD casts (temperature, salinity, nutrients, chlorophyll, oxygen) were available as well as 1519 records of primary productivity measurements and 886 records of taxonomic composition for phytoplankton in the Monterey Bay.

The observed data and the modeled simulated results are compared for each sub-regions, and the statistical analysis has been performed. Overall, the model behavior, in terms of chlorophyll and nitrate concentrations, is quantitatively consistent with observations (high r^2) especially for the off-shore domains. Figure 3 shows the annual mean modeled surface chlorophyll and nitrate for the entire domain. The ROMS-CoSiNE model captures the on- and off-shore contrasts, is able to reproduce the spatial extension of the upwelling system.

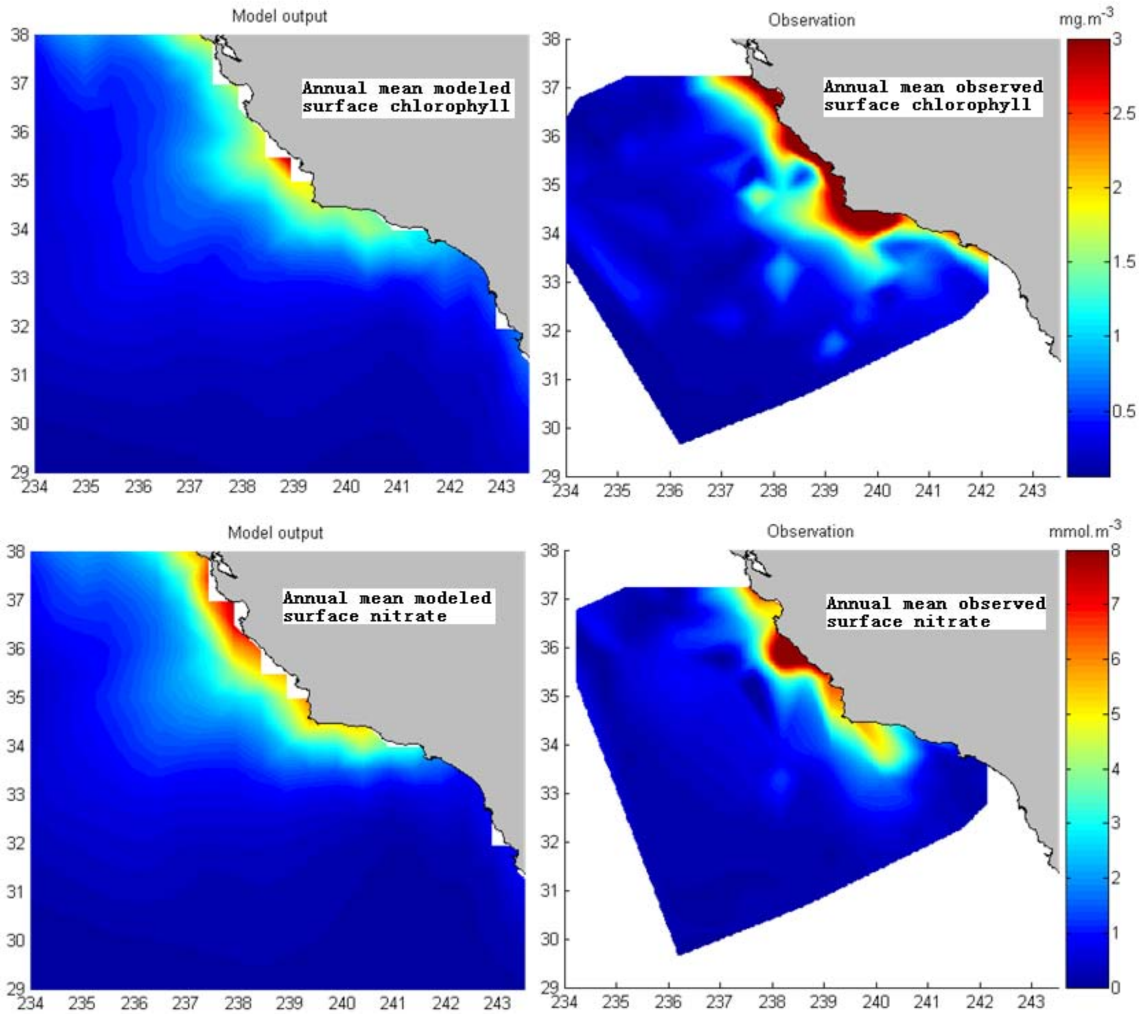

Figure 3: Annual mean modeled surface chlorophyll and nitrate comparisons with the long-term observations (CalCOFI and MBARI), Pawlowski et al. (2008).

Beside the incorporation of the CoSiNE model into the ROMS, we have been collaborating with the Dynamics of Coupled Processes Section (led by Dr. Igor Shulman) at NRL to implement our CoSINE model into the Navy Coastal Ocean Model (NCOM) for the California Current System (CCS). The coupled physical and biological model assimilates remote sensing information, and produces near-real time simulations on regular basis, see Figure 4. The physical-biological model results can be viewed and obtained directly from the NRL website:
http://www7320.nrlssc.navy.mil/ccsnrt/ncomccs-9Km_main.html

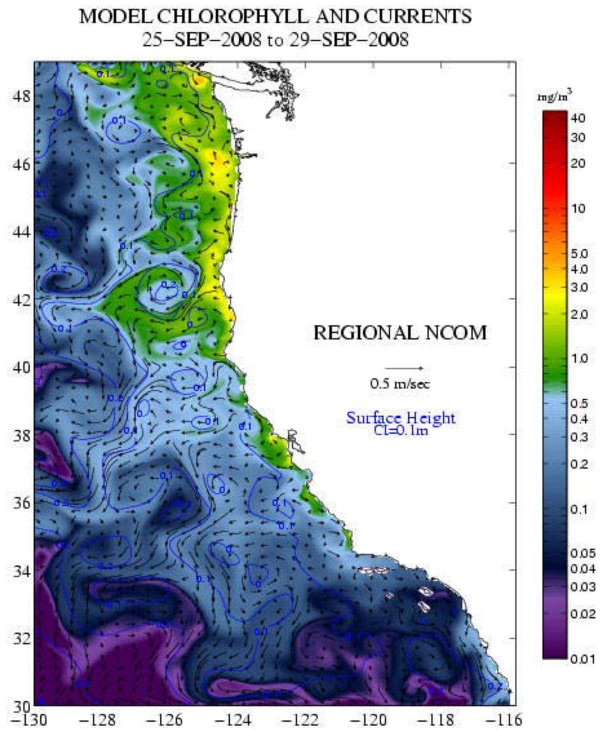

Figure 4: The NCOM-CoSiNE modeled surface currents and chlorophyll for the CCS, 25-29 September 2008.

We use this NCOM-CoSiNE model as our baseline model configuration, and incorporated the optical module into this near real-time modeling system for the CCS. We used the NCOM-CoSiNE model output (chlorophyll, NAP, and POC) for the summer of 2008 (from May to August) to drive an off-line optical output (equations 1 to 6 in this report, and Figure 1). We evaluate the optical properties with the remote sensing derived inherent optical properties (IOPs) based on the quasi-analytical algorithm (QAA) (Lee et al., 2002), Figure 5. Spatial averaged (for the CCS) total absorption a(440) is 0.0489 (m^{-1}) from the model results, and 0.0939 (m^{-1}) for the MODIS data (based on QAA); the phytoplankton absorption $a_{\varphi}(440)$ is 0.0264 (m^{-1}) for the model and 0.0268 (m^{-1}) for the MODIS data; the total backscattering coefficient $b_b(550)$ is 0.0038 (m^{-1}) for the model and 0.0045 (m^{-1}) for the MODIS data. Overall, the optical model produced the IOPs tend to agree well with the MODIS derived results in terms of the magnitude and spatial patterns. (Note that ocean color inversion parameters have an inherent uncertainty of about 50%, IOCCG report 5 edited by Lee). We are analyzing more model results, and improving the optical model performance.

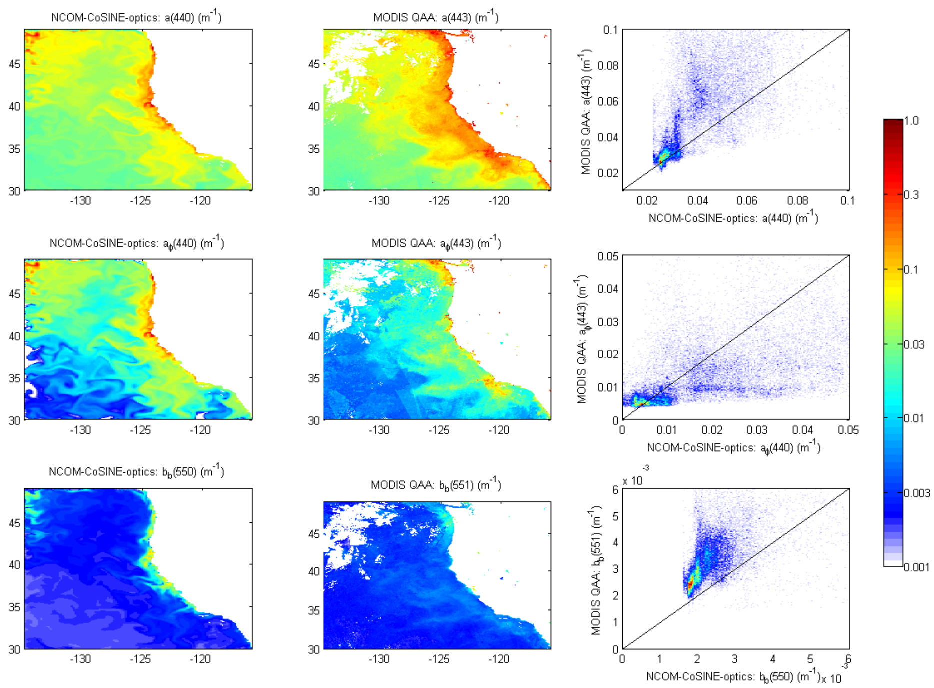

Figure 5: Monthly (June 2008) averaged comparison between the modeled and QAA derived total absorption coefficient at 440 nm, a(440) (the top panel); the phytoplankton absorption coefficient a_{φ}(440) (the middle panel); and total backscattering coefficient at 550 nm b_b(550) (the lower panel). The left column is the NCOM-CoSINE-optics model outputs, the central column is MODIS QAA products, and the right column is the statistical comparison. The color bar is for the left and central columns, has the unit of m^{-1}. The colors in the statistical analysis (the right column) denote the density distribution.

Our current NCOM-CoSiNE model configuration hasn't included the dynamical variation of CDOM in light absorption, instead used a constant absorption coefficient (the equation 2). During the next year of this project, we plan to add dissolved organic matter (DOM) dynamics to the CoSiNE model (note: we have finished that in one-dimensional CoSiNE model configuration, which is flexible enough to be applied to the 3D NCOM and/or ROMS). We will investigate the relation of CDOM and DOM in California Current System focusing on Monterey Bay using observational data to assess how the CDOM-DOM relation changes in space and time. We plan to use the MODIS derived CDOM absorption values to guide and constrain the CDOM performance in our model, Figure 6.

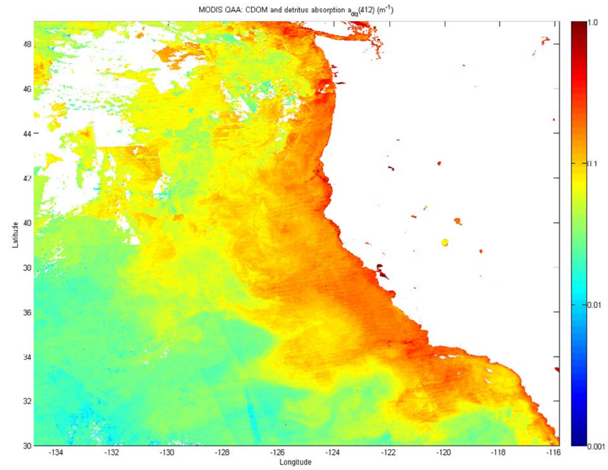

Figure 6: Monthly (June 2008) averaged MODIS QAA derived surface CDOM and detritus absorption coefficient at 412nm (a_{cdm}(412)) for the California Current System. The CDOM absorption is much larger than the detritus component in this estimate.

IMPACT/APPLICATIONS

Incorporating ocean optical processes into coupled physical-biological models will enable us to simulate and forecast optical properties in coastal waters. With demonstration of some initial successes of developing physical-biological-optical modeling and data assimilation capability for the California Current System, we should be able to start the development of an end-to-end ocean forecasting system. Such modeling system would be a powerful tool to design the adaptive sampling strategy and would be an essential component of future field experiments both in and outside Monterey Bay.

TRANSITIONS

We have been working with Drs. John Kindle, Igor Shulman, Bred Penta, and Sergio Derada at the Naval Research Laboratory (NRL). The ecosystem model code has been transferred to the Dynamics of Coupled Processes group (led by Dr. Igor Shulman) at the NRL. Once the optical module is fully tested with the CoSiNE for the CCS, then the optical module along with the updated versio fo CoSiNE model will be transferred to NRL. Fei Chai has scheduled to travel to the NRL in early September of 2008 to work on some issues regarding to the ecosystem component and the optical module in the NCOM, but we had to cancel the meeting due the impact of the Hurricane Gustav. Fei Chai will visit NRL at the end of 2008. We have regular communications between the NRL and the University of Maine on this collaboration.

RELATED PROJECTS

This project has strong collaboration with other ONR supported projects. Besides working closely with the modeling group at the NRL and their BioSpace project, we are collaborating with Dr. Curtis Mobley of Sequoia Scientific Inc. on improving the link between the radiative transfer model (EcoLight) within the NCOM-CoSiNE-Optics. Recently, Dr. Mobley has obtained a grant from ONR to improve the efficiency of the EcoLight calculation in the 3D framework. We are also collaborating with scientists at the Monterey Bay Aquarium Research Institute (MBARI) to use the observational data for the region. Dr. Yi Chao at JPL has been collaborating with us about implementing the CoSiNE into the ROMS for the Pacific Ocean and the CCS.

REFERENCES

Babin, M., D. Stramski, G.M. Ferrari, H. Claustre, A. Bricaud, G. Obolensky, and N. Hoepffner (2003): Variations in the light absorption coefficients of phytoplankton, nonalgal particles, and dissolved organic matter in coastal waters around Europe. Journal of Geophysical Research 108, doi:10.1029/2001JC000882.

Behrenfeld, B., E. Boss, D.A. Siegel, and D.M. Shea (2005): Carbon-based ocean productivity and phytoplankton physiology from space. Global Biogeochemical Cycles 19, doi:10.1029/2004GB002299.

Boss, E., and W.S. Pegau (2001): Relationship of light scattering at an angle in the backward direction to the backscattering coefficient. Applied Optics 40, 5503-5507.

Chai, F., M-S Jiang, Y. Chao, R.C. Dugdale, F. Chavez, and R.T. Barber (2007): Modeling Responses of Diatom Productivity and Biogenic Silica Export to Iron Enrichment in the Equatorial Pacific Ocean. *Global Biogeochemical Cycle*, Vol. 21, GB3S90, doi:10.1029/2006GB002804.

Chai, F., M. Jiang, R.T. Barber, R.C. Dugdale, and Y. Chao (2003): Interdecadal Variation of the Transition Zone Chlorophyll Front, A Physical-Biological Model Simulation between 1960 and 1990. *Journal of Oceanography*, Vol. 59, 461-475.

Chai, F., R. C. Dugdale, T-H Peng, F. P. Wilkerson, and R. T. Barber (2002): One Dimensional Ecosystem Model of the Equatorial Pacific Upwelling System, Part I: Model Development and Silicon and Nitrogen Cycle. *Deep-Sea Res. II*, Vol. 49, No. 13-14, 2713-2745.

Fujii, M., E. Boss, and F. Chai (2007): The value of adding optics to ecosystem models: a case study. Biogeosciences 4, 1585-1631. The paper can be downloaded at the Biogeosciences website: http://www.biogeosciences-discuss.net/4/1585/2007/bgd-4-1585-2007.pdf

Lee, Z., K. L. Carder, and R. A. Arnone, “Deriving inherent optical properties from water color: a multiband quasi-analytical algorithm for optically deep waters,” Applied Optics. 41, 5755-5772 (2002).

Pope, R.M., and E.S. Fry (1997): Absorption spectrum (280-700nm) of pure water. II. Integrating cavity measurements. Applied Optics 36, 8710-8723.

Simeon, J., C. Roesler, W.S. Pegau, and C. Dupouy (2003): Sources of spatial variability in light absorbing components along an equatorial transect from 165^{o}E to 150^{o}W. Journal of Geophysical Research 108, doi: 10.1029/2002JC001613.

Stramski, D., R.A. Reynolds, M. Kahzu, and B.G. Mitchell (1999): Estimation of particulate organic carbon in the ocean from satellite remote sensing. Science, 285, 239-242.